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Research on Atmospheric Attenuation of Infrared Radiation

Howard T. Betz

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FOREWORD

This is the technical report on infrared transmission measurements through fog made at Arcata, California, during September and October 1959 under Contract No. AF 19(604)-5877. This report includes material presented in LAS-TN-E173-5; discussion included in paper presented in AMRAC meeting in Seattle, Washington, on 22 July 1960; and additional reduced transmission data (for which no particle data are available).

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ABSTRACT

This report summarizes the results of a measurement program conducted at Air Force Cambridge Research Center Fog Site at Arcata, California. The purpose of the Arcata fog experiment was (1) to collect data permitting a test of the applicability of Junge's law of the distribution of particle size as a consistent phenomenon of fogs and (2) to verify the predicted values of transmission based upon particle size distribution. The experimental data presented tend to corroborate both Junge's law for particle size distribution and the theory for attenuation using this law.

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1. INTRODUCTION

The principal purpose of this study is to determine the atmospheric attenuation of infrared radiation in a slant path of 5,000 to 40,000 feet in the wavelength range of 1 to 4 microns.

The program was amended to include (1) the determination of the infrared spectral transmission and attenuation through long paths of fog and (2) correlation of the observed attenuation with the density and size distribution of the fog particles and other pertinent physical parameters.

This report summarizes the results of a measurement program conducted at Air Force Cambridge Research Center, Fog Site at Arcata, California.

2. PURPOSE OF EXPERIMENT

The purpose of the Arcata fog experiment was twofold:

(1) To collect data permitting a test of the applicability of Junge's law of the distribution of particle size as a consistent phenomena of fogs which states that

$$n(r) = cr^{-p} \quad , \tag{1}$$

in which $n(r)$ = concentration of particles per unit radius interval; r = radius of particles (microns); and c, p = constants for Junge's law.

(2) To verify the predicted values of transmission based upon particle size distribution [1,2].*

Total scattering at λ due to above distribution is

$$\sigma = \int \pi r^2 K\left(\frac{r}{\lambda}\right) n(r)\, dr \quad ,$$

in which $K(r/\lambda)$ is the scattering coefficient, or

$$\sigma = c\pi \int_{r_0}^{r_1} r^{(2-p)} K\left(\frac{r}{\lambda}\right) dr$$

in which r_0 and r_1 are the smallest and largest radii, respectively, for which Junge's law is valid in a particular fog.

*Numbers in brackets refer to entries in the List of References at the end of this report.

By change of variable to (r/λ), and neglecting the lower limit,

$$\sigma = c\pi\lambda^{(3-p)} \int_0^{r_1/\lambda} \left(\frac{r}{\lambda}\right)^{(2-p)} K\left(\frac{r}{\lambda}\right) d\left(\frac{r}{\lambda}\right) \quad . \tag{2}$$

The values for $K(r/\lambda)$ have been tabulated [3, 4]. The integral in Eq. (2) can, in general, be integrated numerically and tables of σ as a function of λ, p, c, and r_1 can be devised. The parameters p, c, and r_1 can be measured experimentally.

3. EXPERIMENTAL PROCEDURE

To test the above relations, the experimental work was divided into two phases:

(1) Direct measurement of particle size distribution.

(2) Measurement of the fog transmission as a function of wavelength.

The particle size measurement was made with the Cambridge Research Center's cloud particle counter constructed by the Armour Research Foundation. This device counts particles and classifies them according to size by the light scattered from individual particles. Particles are classified into six sizes: 1 to 2, 2 to 4, 4 to 8, 8 to 16, 16 to 32, and larger than 32 microns in diameter.

Wherever possible the particle count data and transmission measurements were taken concurrently, and the particle counter was located adjacent to the optical path

Spectral measurements were made with essentially that equipment used by Kurnick et. al. [1]. The source, located in a small trailer, was a carbon arc with a 12-1/2 inch, f/5 collimator. The receiver was a Perkin-Elmer double-pass monochromator with a 12-1/2 inch, f/5 collector, and was located in a semi-trailer 200 yards from the source. The interval chopper of the monochromator was modified to give an 80-cps chopping rate. The detector was a 0.1- by 0.1-mm thermistor bolometer. Bandwidth of the amplifier was 20 cycles centered at 80 cps. The final record was made on an x-y recorder with the detector output on the x-axis and monochromator wavelength drum position on the y-axis. Using a sodium-chloride prism the instrument scanned from 1.5 to 12 microns in approximately 4 minutes. The slit width was varied to maintain a reasonable power level on the detector; i.e., the radiant power on the detector was maintained within a factor of 100 to 1. Figure 1 shows the actual variations in power level.

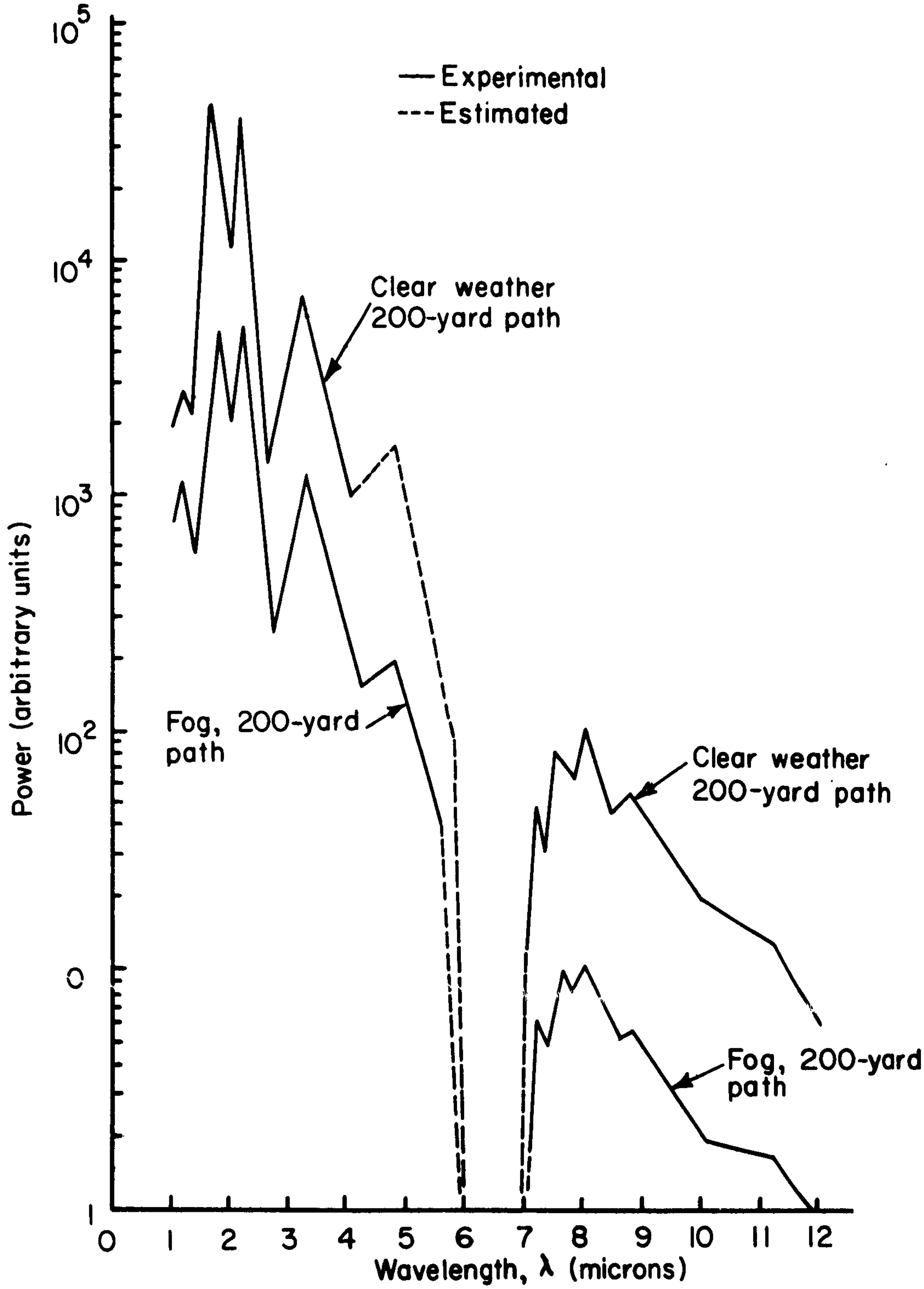

Figure 1. Typical Record of Normalized Spectrum of Carbon Arc Observed through a 200-yard Path in Clear Weather and Fog.

4. DISCUSSION OF RESULTS

The results of the particle size measurements are shown in Table 1 for fog data taken on 16 October 1959. (The particle counter was delivered on 12 October, but it was not until 16 October that the instrument was operating satisfactorily; hence, this is the only day for which reliable data are available. Transmission data and other parameters such as wind direction are given for all days in Tables 2 and 3. The measurements of visibility were taken at the National Bureau of Standard's visibility range about 500 yards from the infrared transmission path.)

The values for particle size are given in terms of the number of particles per cubic centimeter for size intervals of 0.5 to 1.0, 1.0 to 2.0, 2.0 to 4.0, 4.0 to 8.0, and 8.0 to 16.0 microns in radius. The columns are labeled with the mean radius of each interval; i.e., 0.75, 1.5, 3, 6, and 12 microns.

Junge's law, Eq. (1), was checked by plotting $n(r)\,\Delta r$, the number of particles per unit volume in radius interval Δr, against the mean particle radius in the interval on a logarithmic scale (see Figure 2). The negative slope of this curve is the value of p. Since a straight line can be drawn through the points in Figure 2, Junge's law applies to this fog.

An attempt was made to correlate the transmission observed through fog with Eq. (2) using the values of p, c, and r obtained from the analysis of the aerosol data. This equation, in principle, gives the absolute transmission as a function of wavelength. However, it is not directly useful for several reasons:

(1) The transmission T is dependent on c. (Note that $\ln(1/T) = \sigma L$, where L is the path length.) Since sampling was made at a fixed point near the path, considerable variation in concentration may exist. Hence, correlation between the overall transmission and concentration is doubtful.

(2) The use of a carbon arc which required readjustment at intervals may easily have disturbed the alignment of the system. Therefore, the absolute value of the measured transmission may not be accurate. The relative values for various wavelengths during a single run are not affected; thus, the shapes of the curves on a log plot of transmission are accurate.

An alternative approach was used to make the correlation. Equation (3), derived by differentiation from Eq. (2), is independent of the value of c. It is related to the shape of the experimental curve of log log reciprocal transmission vs. log λ by Eq. (4).

$$\frac{d(\ln \sigma)}{d(\ln \lambda)} = (3 - p) - \frac{r_1^{(3-p)} K\left(\frac{r_1}{\lambda}\right)}{\int_0^{r_1/\lambda} \left(\frac{r}{\lambda}\right)^{(2-p)} K\left(\frac{r}{\lambda}\right) d\left(\frac{r}{\lambda}\right)} \quad . \tag{3}$$

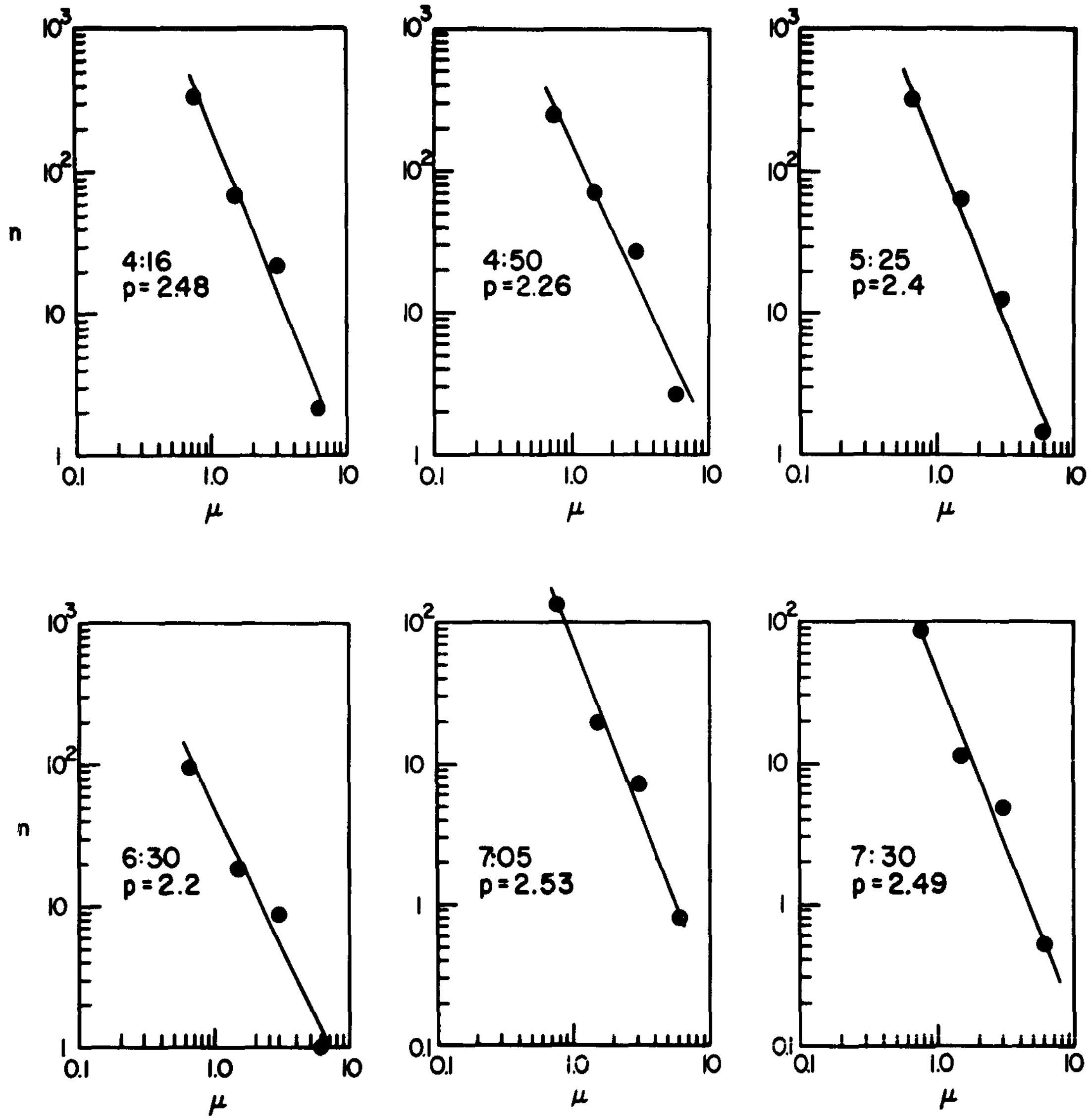

Figure 2. Selected Plots of n(r) vs r for Fog on the Morning of 16 October 1959.

$$\frac{d(\ln \sigma)}{d(\ln \lambda)} = \frac{d\left(\ln \ln \frac{1}{T}\right)}{d(\ln \lambda)} = \frac{d\left(\log \log \frac{1}{T}\right)}{d(\log \lambda)} \quad (4)$$

The values of p and r_1 should be the same throughout the fog. The second term on the right in Eq. (3) is of interest. For $p > 3$ and a particular r_1, this term is dependent on p and only slightly dependent on λ (or r_1/λ). For decreasing values of $p < 3$, this term develops a "ripple" becoming increasingly dependent on r_1/λ. Since r_1 is at best an approximate value, a smoothed value should be used for $[d(\ln \sigma)]/[d(\ln \lambda)]$. The resulting smoothed value becomes positive for $2.2 < p < 2.7$ (in the region $(r_1/\lambda) >> 1$). In this range of r_1/λ, the slope of the transmission data is zero or slightly positive (note dotted lines in Figure 3). For $(r_1/\lambda) < 1$ (Rayleigh scattering), $[d(\ln \sigma)/[d(\ln \lambda)]$ is always strongly negative and one should expect a rapid increase in transmission (decrease in ln ln 1/T). Such a change to increasing transmission occurs in the experimental data at about 10 microns, again, see Figure 3. The most to be said about r_1 from the experimental particle data is that it lies between 8 and 16 microns.

Therefore, within the limits of accuracy of the equipment, the experimental data tends to corroborate both Junge's law for particle size distribution and the theory for attenuation using this law.

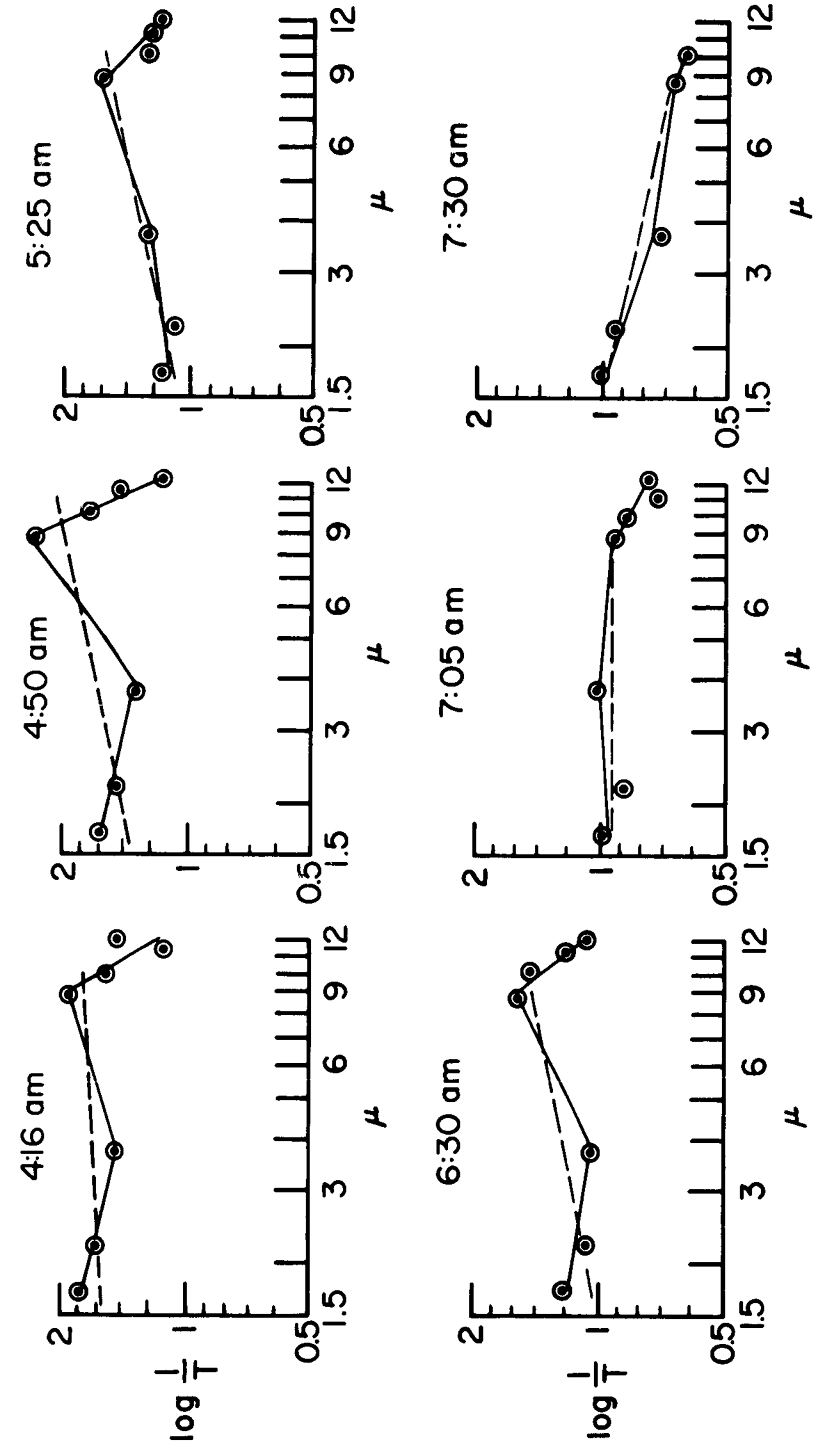

Figure 3. Selected Plots of Log $\frac{1}{T}$ vs λ for Fog of 16 October 1959.

Table 1. Particle Size and Transmission Measured in Fog on 16 October 1959 at Arcata, California

Time	Number of Particles per cm^3 per Unit Radius Interval $\overline{n}(r)$*					p	$\log\left(\frac{1}{T}\right)$						
	r = 0.75μ	r = 1.5μ	r = 3μ	r = 6μ	r = 12μ		λ = 1.7μ	λ = 2.2μ	λ = 3.7μ	λ = 8.8μ	λ = 10μ	λ = 11.2μ	λ = 12μ
4:00 A.M.	275	71.5	21.2	1.59	0.000022	2.48	1.58	1.47	1.43	1.74	1.64	1.21	1.17
4:10 A.M.	--	--	--	--	--	--	1.70	1.62	1.28	1.70	1.60	1.33	1.28
4:16 A.M.	332	67.7	21.2	2.12	0.0088	2.48	1.77	1.60	1.49	1.89	1.52	1.20	1.46
4:35 A.M.	332	60.5	31.8	2.68	0.0048	2.44	--	--	1.08	2.05	1.52	1.33	1.28
4:45 A.M.	314	57	23	2.6	0.003	2.45	1.66	1.50	1.50	2.04	1.85	1.35	1.48
4:50 A.M.	237	66.7	25.9	2.6	0.0013	2.26	1.60	1.46	1.29	2.30	1.52	1.41	1.15
5:00 A.M.	373	69.6	25.3	1.49	0.003	2.39	1.72	1.64	1.59	1.96	1.60	1.51	1.28
5:10 A.M.	184	53.0	21.6	2.11	0.0008	2.15	1.73	1.55	1.56	2.05	1.70	1.51	1.28
5:15 A.M.	250	50.0	12.5	1.56	0.003	2.62	1.52	--	1.28	2.05	1.47	1.33	1.16
5:25 A.M.	319	64.4	12.8	1.42	0.0008	2.4	1.17	1.10	1.26	1.58	1.24	1.21	1.17
5:30 A.M.	287	62.2	13.2	1.8	0.0035	2.4	1.34	1.11	1.18	1.70	1.31	1.20	1.28
5:40 A.M.	213	38.3	7.91	1.12	0.0004	2.64	1.24	1.09	1.00	1.44	1.32	1.12	0.996
5:50 A.M.	265	59.4	14.9	1.66	0.0015	2.44	1.47	1.42	1.30	1.66	1.32	1.12	--
6:00 A.M.	254	52.4	8.56	1.01	0.0006	2.69	1.15	1.04	1.14	1.51	1.41	1.26	1.06
6:10 A.M.	236	48.7	8.11	0.89	0.0009	3.00	1.48	1.40	1.41	1.57	1.55	1.17	--
6:20 A.M.	139	36.3	15.2	2.10	0.0009	2.07	1.02	0.958	1.00	1.16	1.15	0.946	0.924
6:30 A.M.	95.1	18.5	8.81	1.02	0.00044	2.20	1.22	1.09	1.08	1.57	1.48	1.22	1.07
6:40 A.M.	178	36.9	8.52	0.923	0.00263	2.56	0.793	0.766	0.743	1.06	1.03	0.872	0.801
6:45 A.M.	168	32.3	9.12	1.12	0.0026	2.42	0.876	0.787	0.681	1.07	0.924	0.688	0.757
7:05 A.M.	130	19.3	7.12	0.788	0.0013	2.53	0.987	0.893	1.01	0.906	0.860	0.721	0.757
7:20 A.M.	100	11.2	4.48	0.588	0.0013	1.99	--	--	0.743	--	--	--	--
7:30 A.M.	84.9	11.1	4.90	0.506	0.0004	2.49	1.01	0.916	0.711	0.657	0.625	0.167	--
7:45 A.M.	34.5	4.24	3.48	0.499	0.0000	2.22	0.951	0.854	0.857	0.991	1.022	0.886	0.866
"Clear" 2:15 P.M.	23	3.45	0.78	0.056	0.000	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00

*Note that $\overline{n}(r)$ is an average value derived by measuring the concentration of particles in radius interval Δr and dividing by the radius interval.

Table 2. Experimental Transmission and Particle Count in Fog on 16 October 1959.

Time	Per cent of Transmission, Wavelengths in Microns							Particles* per cm^3	Percentage of Particles Between Noted Sizes					Visible Transmission (per cent)	Wind Velocity	Wind Direction (degrees)	Temperature (degrees centigrade)
	1.7	2.2	3.7	8.8	10	11.2	12		1-2μ	2-4μ	4-8μ	8-16μ	16-32μ				
4:00 A. M.	2.6	3.4	3.7	1.8	2.3	6.1	6.8	265	54	27	16	2.4	0.0067	19	3	190	11
4:10 A. M.	2.0	2.4	5.3	2.0	2.5	4.7	5.3	--	--	--	--	--	--	--	--	--	11
4:16 A. M.	1.7	2.5	3.2	1.3	3.0	6.3	3.5	282	59	24	15	3.0	0.0025	11	4	150	11
4:35 A. M.	--	--	8.0	0.9	3.0	4.7	5.3	303	55	20	21	3.6	0.0128	10	3.5	115	11
4:45 A. M.	2.2	3.2	3.1	0.89	1.4	4.5	3.3	270	58	21	17	3.8	0.009	12	2	135	11
4:50 A. M.	2.5	3.5	5.1	0.5	3.0	3.9	7.0	247	48	27	21	4.2	0.0043	22	2	100	11
5:00 A. M.	1.9	2.3	2.6	1.1	2.5	3.1	5.3	316	59	22	16	2.2	0.0078	14	2.5	115	11
5:10 A. M.	1.9	2.8	2.8	0.9	2.0	3.1	5.3	196	47	27	22	4.3	0.0018	27	2.5	60	11
5:15 A. M.	3.0	--	5.3	0.9	3.4	4.7	7.0	208	60	24	12	3.0	0.0118	31	2.5	325	11
5:25 A. M.	6.8	8.0	5.5	2.6	5.7	6.1	6.8	267	62	25	10	2.6	0.00268	30	2.5	270	11
5:30 A. M.	4.6	7.7	6.6	2.0	4.9	6.3	5.3	239	60	26	11	3.0	0.01179	32	2.5	Shifting	11
5:40 A. M.	5.8	8.2	10.0	3.6	4.8	7.6	10.1	166	64	23	9.5	2.7	0.00211	21	2.5	Variable	11
5:50 A. M.	3.4	3.8	5.0	2.2	4.8	7.5	--	228	58	26	12	3.0	0.0052	36	2.5	Variable	11
6:00 A. M.	7.1	9.2	7.3	3.1	3.9	5.5	8.8	201	63	26	8.5	2.0	0.0025	30	2.5	45	11
6:10 A. M.	3.3	4.0	3.9	2.7	2.8	6.8	--	188	63	26	9.0	1.9	0.0018	25	2	70	11
6:20 A. M.	9.5	11.0	10.0	6.9	7.1	11.3	11.9	145	48	25	21	5.8	0.0048	20	2.5	105	11
6:30 A. M.	6.1	8.2	8.3	2.7	3.3	6.1	8.5	88	54	21	20	5.8	0.004	40	3.0	90	11
6:40 A. M.	16.0	17.0	18.0	8.8	9.4	13.4	15.8	142	63	23	12	2.6	0.0074	42	1.5	250	11
6:45 A. M.	13.2	16.3	21.0	8.5	11.8	20.5	17.5	140	60	23	13	3.2	0.015	46	1.5	190	11
6:55 A. M.	--	--	--	14.6	17.7	21.3	29.8	--	--	--	--	--	--	--	--	--	11
7:05 A. M.	10.3	12.8	9.8	12.4	13.8	19.0	17.5	102	64	19	14	3.1	0.010	44	3.0	135	11
7:20 A. M.	--	--	18.0	--	--	--	--	73	69	15.4	6.9	3.2	0.0143	60	3.5	150	11
7:30 A. M.	9.7	12.1	19.5	22.6	23.7	68.0	--	65	65	17	15	3.1	0.0054	74	3.9	95	11
7:45 A. M.	11.2	14.0	13.9	10.2	9.5	13.0	13.6	32	57	14	23	6.6	0.000	25	2	160	11
7:50 A. M.	0.68	1.0	--	0.7	0.95	1.5	2.0	--	--	--	--	--	--	--	2.4	135	11
2:15 P. M.	100	100	100	100	100	100	100	16	72.4	22	4.9	.25	0.000	95	5	300	11

*Particles were counted for a period of 3 minutes beginning at each time listed. Total number of particles counted varied from 4000 to 90,000 in the 3-minute interval.

Table 3. Experimental Infrared Transmission through Fog.

Time	Per cent of Transmission Wavelengths in Microns						Visible Transmission (Per cent)	Wind Velocity	Wind Direction*
	1.7	2.2	8.8	10	11.2	12			
3 October 1959									
4:35 P.M.	0.70	0.80	no measurable transmission	no measurable transmission	no measurable transmission	no measurable transmission	2	6	
4:45 P.M.	0.26	0.17					2	3	
4:50 P.M.	0.19	0.23					4	3	
5:05 P.M.	0.03	0.04					2	2.5	
5:20 P.M.	0.02	0.02					2	2	
7:10 P.M.	0.01	0.00					1	5	
7:15 P.M.	0.01	0.01					1	2.5	
7:25 P.M.	0.02	0.02					1	5	
7:30 P.M.	0.01	0.01					1	5	
7:40 P.M.	0.01	0.01					1	5	
7:45 P.M.	0.00	0.00					1	5	
8:05 P.M.	0.01	0.01					1	3	
8:30 P.M.	0.02	0.02					1	4	
9:35 P.M.	0.60	0.80					2	3	
9:50 P.M.	0.08	0.10					2	3	
10:15 P.M.	0.07	0.10					2	3	
10:20 P.M.	0.08	0.11					6	3	
10:45 P.M.	0.11	0.15					2	5	
4 Oct.59 3:30 P.M.	100	100	100	100	100	100	95	2.5	

*Wind direction can be obtained from the National Bureau of Standards installation at Arcata, California.

Table 3 (continued)

Time	Per cent of Transmission, Wavelengths in Microns						Visible Transmission (Per cent)	Wind Velocity	Wind Direction*
	1.7	2.2	8.8	10	11.2	12			
8 October 1959									
9:10 A.M.	150	160	150	190	140	150	85	6.5	
9:25 A.M.	120	140	73	57	71	60	82	5	
9:55 A.M.	93	100	81	100	77	70	90	4	
10:05 A.M.	100	100	100	100	100	100	91	3.5	
9 October 1959									
7:30 A.M.	--	--	10	6.4	7.3	5.0	--	10	
7:55 A.M.	85	93	--	57	88	52	52	9	
8:20 A.M.	92	93	100	67	71	29	56	8.5	
8:40 A.M.	170	170	106	39	139	95	72	11.5	
8:50 A.M.	41	44	17	21	23	6.7	40	10	
9:00 A.M.	108	123	32	38	21	13	35	8	
9:10 A.M.	2.6	2.7	1.2	4.5	7.2	6.7	36	6.5	
9:20 A.M.	9.7	9.5	4.1	9.6	12.5	10.1	10	5	
9:30 A.M.	2.0	2.4	1.5	7.1	9.4	6.7	6	4	
9:40 A.M.	1.8	2.1	1.7	10.6	11.5	8.4	6	13.5	
9:50 A.M.	2.0	2.3	7.8	32	25	25	--	4.5	
9:55 A.M.	23	25	5.9	74	60	52	30	3.5	
10:10 A.M.	26	28	34	55	68	39	25	3.5	
10:15 A.M.	--	--	78	86	85	56	20	2.5	
10:25 A.M.	74	94	123	159	162	139	70	6.5	
10:35 A.M.	180	200	161	172	193	168	80	7.5	
10:55 A.M.	155	167	118	125	143	143	70	6.5	
11:00 A.M.	152	162	169	129	126	120	80	7.5	
11:10 A.M.	169	195	250	195	205	196	80	10.0	
4:30 P.M.	134	150	104	108	130	105	96	2.5	
4:35 P.M.	100	100	100	100	100	100	94	1.5	

Table 3 (continued)

Time	Per cent of Transmission, Wavelengths in Microns						Visible Transmission (Per cent)	Wind Velocity	Wind Direction*
	1.7	2.2	8.8	10	11.2	12			
12 October 1959									
7:25 A.M.	6.8	6.6	1.7	2.3	4.9	5.6	5	--	
7:35 A.M.	6.0	6.4	2.8	0.6	1.0	1.9	3	--	
7:45 A.M.	1.7	1.8	0.92	0.6	2.0	4.7	4	--	
7:55 A.M.	2.8	3.1	4.9	4.3	6.9	7.5	--	--	
8:05 A.M.	9.0	10.0	23	37	51	46	34	--	
8:15 A.M.	40.0	37	35	39	56	49	40	--	
8:25 A.M.	54	57	64	46	104	121	90	--	
8:30 A.M.	96	92	62	120	74	87	92	--	
8:40 A.M.	100	100	100	100	100	100	96	--	
14 October 1959									
9:15 P.M.	0.007	0.021	no measurable transmission	no measurable transmission	no measurable transmission	no measurable transmission	0	5	108
9:50 P.M.	0.12	2.17					0	1.5	180
12:05 A.M.	0.019	0.034					0	5.5	162
12:30 A.M.	0.013	0.029					0	4.0	144
12:40 A.M.	0.016	0.036					0	5.0	139
12:55 A.M.	0.106	0.158					0	3.0	45
1:00 A.M.	0.052	0.090					0	2.0	66
1:10 A.M.	0.213	0.415					2	3.0	54
2:20 A.M.	0.065	0.131					2	3.0	95
2:30 A.M.	0.008	0.045					0	3.5	171
2:40 A.M.	0.009	0.025					0	15.0	147
2:50 A.M.	0.008	0.016					0	3.0	135
3:00 A.M.	0.032	0.068					0	2.0	216
3:05 A.M.	0.007	0.010					0	3.0	167
3:15 A.M.	0.011	0.013					0	3.0	176
3:25 A.M.	0.010	0.023					0	1.5	202
16 Oct.59 2:15 P.M.	100	100	100	100	100	100	95	5	300

LIST OF REFERENCES

1. Kurnick, S. W., Zitter, R. N., and Williams, D. B., Atmospheric Transmission in the Infrared During Severe Weather Conditions. The University of Chicago, Laboratories for Applied Sciences, Report No. CML-TN-P145-3, May 1959 (Unclassified).

2. Kurnick, S. W., Zitter, R. N., and Williams, D. B., "Attenuation of Infrared Radiation by Fogs" JOSA, 50:6 (June 1960) 578-583.

3. Gumprecht-Sliepcevich, Light Scattering Functions for Spherical Particles, The University of Michigan, 1951.

4. Penndorf, R., "Mie Scattering Coefficient for Water Droplets in Air," Meteorol., 13: 2(1956) 219.

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AF Cambridge Research Center, Bedford, Mass. RESEARCH ON ATMOSPHERIC ATTENUATION OF INFRARED RADIATION, by Howard T. Betz. Dec 1960. 13 pp incl. illus. (Proj. 4991; Task 49910) LAS-TN-E173-10 (AF 19(604)-5877)

Unclassified Report

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